Synopsis of Precision Landing and Hazard Avoidance (PL&HA) Capabilities for Space Exploration

Abstract

Until recently, robotic exploration missions to the Moon, Mars, and other solar system bodies relied upon controlled blind landings. Because terrestrial techniques for terrain relative navigation (TRN) had not yet been evolved to support space exploration, landing dispersions were driven by the capabilities of inertial navigation systems combined with surface relative altimetry and velocimetry. Lacking tight control over the actual landing location, mission success depended on the statistical vetting of candidate landing areas within the predicted landing dispersion ellipse based on orbital reconnaissance data, combined with the ability of the spacecraft to execute a controlled landing in terms of touchdown attitude, attitude rates, and velocity. In addition, the sensors, algorithms, and processing technologies required to perform autonomous hazard detection and avoidance in real time during the landing sequence were not yet available. Over the past decade, NASA has invested substantial resources on the development, integration, and testing of autonomous precision landing and hazard avoidance (PL&HA) capabilities. In addition to substantially improving landing accuracy and safety, these autonomous PL&HA functions also offer access to targets of interest located within more rugged and hazardous terrain. Optical TRN systems are baselined on upcoming robotic landing missions to the Moon and Mars, and NASA JPL is investigating the development of a comprehensive PL&HA system for a Europa lander. These robotic missions will demonstrate and mature PL&HA technologies that are considered essential for future human exploration missions. PL&HA technologies also have applications to rendezvous and docking/berthing with other spacecraft, as well as proximity navigation, contact, and retrieval missions to smaller bodies with microgravity environments, such as asteroids.

Introduction

Until recently, robotic exploration missions to the Moon, Mars, and other solar system bodies relied upon controlled blind landings. Because terrestrial techniques for terrain relative navigation (TRN) had not yet been evolved to support space exploration, landing dispersions were driven by the capabilities of inertial navigation systems combined with surface relative altimetry and velocimetry. Lacking tight control over the actual landing location, mission success depended on the statistical vetting of candidate landing areas within the predicted landing dispersion ellipse based on orbital reconnaissance data, combined with the ability of the spacecraft to execute a well-controlled landing in terms of touch down attitude, attitude rates, and velocity.

The core guidance, navigation, and control (GN&C) capabilities essential for achieving a controlled landing also serve as the foundation for the incorporation of modular, autonomous PL&HA capabilities on future robotic and human exploration vehicles. Autonomous precision landing can be achieved by blending map-based TRN measurements into the core navigation filter architecture. Autonomous hazard detection and avoidance can be achieved by generating a high-resolution local terrain map during the descent trajectory. The spacecraft guidance system must then execute a divert maneuver and touch down in close proximity to the selected safe landing target. The integration of these functions results in a controlled, precise, and safe landing, as shown in the Venn diagram in Figure 1.

Inputs from external navigation aids, such as navigation satellites and passive or active surface beacons, can be blended into this GN&C architecture as they become available.

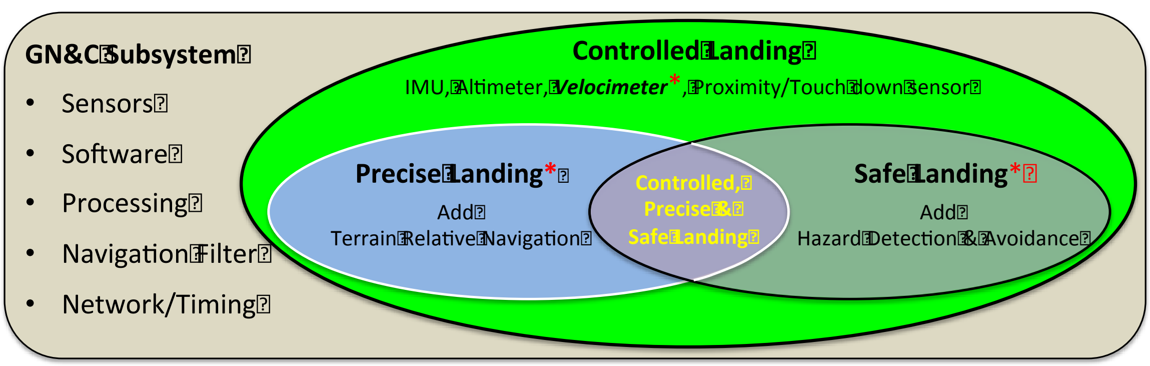

Figure 1 – PL&HA Venn Diagram

The addition of precision landing and/or hazard avoidance functions will provide mission planners and spacecraft engineers with important new capabilities:

- Enhanced probability of safe landing and overall mission success
- Improved access to landing sites of scientific, programmatic, or industrial interest located within challenging terrain

- Proximity landing relative to surface features such as craters, rocky outcrops, alluvial deposits, or openings to underground formations
- Coordinated landings to support multi-mission exploration campaigns or natural resource prospecting and mining efforts
- Improved risk posture for landing missions to uncharacterized or poorly characterized solar system destinations

The preferred PL&HA implementation for a given mission depends on a range of considerations including mission risk tolerance, availability and quality of reconnaissance data, landing site characteristics, mission design and objectives, lander design/scale, and program budget and schedule.

Background

The NASA Autonomous Landing and Hazard Avoidance Technology (ALHAT) project was chartered in 2006 to develop and mature PL&HA sensors and algorithms applicable to crewed, cargo, and robotic planetary landing missions.[i,ii] ALHAT capabilities have been demonstrated in numerous field test campaigns using airplanes, helicopters, and rocket-powered Vertical Test Beds (VTBs), concluding with three closed loop free flights on the Morpheus lander at the KSC Shuttle Landing Facility in 2014.[iii,iv]

NASA has invested significant resources at multiple centers and contractors for PL&HA simulation, development, integration, and testing to mature the following capabilities:

- Terrain Relative Navigation (TRN) using passive and active sensors to improve map-based navigation
- Advanced lidar navigation sensors providing signficant improvements in the accuracy and precision of surface relative ranging and velocity measurements
- Long range 3-D flash lidar sensor for the rapid generation of large, high resolution terrain models during the descent and landing trajectory
- Hazard Detection (HD) algorithm to identify and prioritize safe landing sites from the 3-D terrain model
- Hazard Relative Navigation (HRN) algorithm to maintain an accurate spacecraft position estimate relative to the selected safe landing site
- Advanced navigation filter integating inertial and surface-relative measurements
- Adaptive guidance algorithm to efficiently execute divert maneuvers during descent and landing

Following ALHAT Field Test #3 in 2009, which demonstrated both passive optical and lidar-based TRN approaches in flights over the Nevada Test Site and Death Valley, JPL continued refining its optical TRN strategy with the development of the Lander Vision System (LVS). LVS was successfully tested on the Masten

Space Systems Xombie vehicle in 2014, and was subsequently baselined for inclusion on the NASA Mars 2020 mission. In parallel, JHUAPL continued developing and refining APLNav as part of the Mighty Eagle VTB effort at MSFC. APLNav is a passive optical TRN approach optimized for small robotic landers and engineered to enable co-hosting on the primary spacecraft CPU. APLNav is currently baselined on the NASA Resource Prospector mission. JPL is currently engaged in a Europa lander mission study with the objective of incorporating a comprehensive PL&HA system dubbed the Intelligent Landing System (ILS).

Following the conclusion of the Morpheus-ALHAT free flight campaigns, the sensor team at NASA LaRC continued evolving the ALHAT Navigation Doppler Lidar (NDL) sensor, which generates simultaneous, high precision, line of sight range and velocity measurements along three separate beams. The NDL sensor assists in developing and maintaining a highly accurate navigation state during the final few kilometers of descent. During Morpheus-ALHAT Free Flight #15, the second generation NDL sensor demonstrated a velocity precision of 0.017 m/s (3σ). An autonomous navigation system combining the JPL LVS with the third generation NDL sensor will be tested on the CoOperative Blending of Autonomous Landing Technologies (COBALT) flights in 2017. The COBALT flights on the Masten Space Systems Xodiac VTB will demonstrate an integrated precision navigation capability applicable to a wide range of lander missions, both human and robotic. The forward plan is to build on this precision navigation foundation by adding a terrain mapping lidar sensor with electronic beam steering to support real-time hazard detection.

Precise, Safe, and Controlled Landings

Terrain Relative Navigation (TRN)

Mission designers employ orbital reconnaissance data to statistically vet potential landing areas for landing hazards and to select map-based landing targets in proximity to sites of scientific interest. As illustrated in Figure 2, the quality and resolution of reconnaissance data has gradually improved over the years for Mars and other solar system destinations. However, lander GN&C systems must also evolve to take full advantage of the improved reconnaissance data.

Figure 2 – Evolution of Mars Orbital Reconnaissance Imagery

If *a priori* orbital reconnaissance data for a particular destination is not available

or is of insufficient quality, then it may be possible to collect the required terrain information during a mission by including an orbital mapping phase. The data would be sent to Earth for processing and the TRN maps and landing target would be uploaded to the spacecraft. The same approach could be employed for destinations at which the surface geometry varies over time, such as icy moons. In those cases, it may only be necessary to spot check older reconnaissance data to verify key landmarks and the condition of the targeted landing site.

Landing dispersion ellipses relative to a map-based target have historically varied from roughly one kilometer at the Moon to tens of kilometers or greater at Mars. Key factors driving the size of the landing dispersion ellipse include the spacecraft entry, descent, and landing (EDL) strategy, navigation state accuracy at entry interface or the initiation of powered descent, presence or absence of an atmosphere, and knowledge of the planetary gravitational field.

Terrain Relative Navigation (TRN) is an essential technology for leveraging high resolution reconnaissance data to improve landing accuracy for future human and robotic exploration missions. TRN formulations are available to generate position, attitude, or velocity measurements, or some combination of those state elements. Early TRN position updates enable a spacecraft to efficiently eliminate navigation errors during the EDL trajectory. The accuracy of TRN position measurements is limited by the quality and resolution of the reconnaissance map, as well as its registration within the global coordinate frame. Using TRN position updates, a spacecraft can achieve pinpoint landing at a specific, map-based location on a planetary surface, or simply divert to a more favorable landing region within the landing dispersion ellipse. TRN velocity measurements can be obtained independent from *a priori* reconnaissance maps using optical flow techniques that track frame-to-frame feature displacements to estimate relative spacecraft motion.

TRN can be performed using active range sensors or passive optical cameras. Active radar and lidar sensors have the advantage of providing direct range measurements. Active sensors also function under any ambient lighting conditions, even total darkness, thus providing greater flexibility in mission design. While existing radar and lidar sensors are heavier and require more power than passive sensors, it should be noted that lidar sensors are still at a relatively early stage of development. It is anticipated that lidar sensors will gradually become more competitive in terms of size, weight, and power (SWaP) given continued advancements in laser-related technologies. Passive optical cameras have an extensive spaceflight heritage and are a very attractive option for TRN, especially for robotic landers, due to their lower SWaP requirements. Space-qualified passive optical cameras and components are also commercially available at relatively low cost.

Lidar-based TRN approaches use altitude profile matching or contour correlation to a 3-D Digital Elevation Model (DEM) developed from orbital reconnaissance data. Since lidar TRN approaches utilize 3-D data, some degree of variability in

terrain elevation is required to achieve satisfactory correlation results. Passive optical TRN commonly operates by matching landmarks in an intensity image to corresponding landmarks registered in reconnaissance imagery. Passive optical TRN has been demonstrated to function quite well even in terrain that appears flat and relatively featureless to the human eye. But passive optical TRN performance is adversely impacted by poor lighting conditions (long or deep shadows), poor image contrast or exposure, and other variations between the *a priori* orbital reconnaissance data and the images obtained by the onboard cameras. Although this is not an issue for the Moon or Mars, terrestrial field tests have shown that shadows cast by clouds can also be problematic for passive optical TRN. The performance of both lidar-based and passive optical TRN is adversely impacted by photon scattering and attenuation from particulates suspended in the planetary atmosphere. Otherwise, the passive and active lidar TRN techniques tend to complement each other in terms of strengths and weaknesses.

At both the global and local scale, landing safety is coupled to landing accuracy and precision. The precision of the TRN measurement has a first-order impact on the spacecraft navigation state and drives the minimum allowable size of a safe landing site. TRN enhances landing safety by enabling a lander to accurately target a specific area deemed to be favorable for landing, or by supporting a local divert maneuver to avoid regions within an entry dispersion ellipse that are statistically more hazardous. If the entry dispersion ellipse is large, then the latter technique can be accomplished with far less propellant. For this reason, the Lander Vision System (LVS) baselined on the upcoming Mars 2020 mission is used to bias the lander backshell avoidance maneuver in a direction favorable to landing safety. However, even this simple application of TRN can materially improve the probability of a safe landing by avoiding the larger, known hazards.

<u>Hazard Detection and Avoidance (HDA)</u>

Hazard detection and avoidance can be applied in a blind landing scenario, but the probability of locating a safe landing site is enhanced when TRN is employed to position the lander in proximity to terrain already vetted by mission planners. The terrain vetting process eliminates the larger hazards detectable in the reconnaissance data, resulting in an increased likelihood of identifying at least one safe landing site within the HDEM boundary. For smaller robotic spacecraft with footprints up to a few meters in diameter, the addition of TRN, alone, provides a significant advancement in performance in terms of both landing site accessibility and the probability of safe landing. However, relative to a fixed set of landing conditions – terrain characteristics, lander hazard tolerance and stability, and touch down velocity, attitude, and attitude rates – landing risks grow in a non-linear fashion as the lander footprint increases. Even the best available orbital reconnaissance data for the Moon and Mars is insufficient to reliably resolve surface roughness features on a sub-meter scale. In addition, as the lander footprint grows, it becomes increasingly difficult to locate a safe landing site of sufficient dimensions to envelope the lander footprint plus GN&C dispersions, especially in more hazardous terrain. Furthermore, the mission risk

posture is much more stringent for crew and cargo missions than for robotic missions. These considerations lead to the next step in the autonomous PL&HA architecture – the addition of real-time, onboard hazard detection and avoidance.

Large landers suitable for the delivery of astronauts and cargo will require both controlled, precision landing and some form of hazard avoidance. The ALHAT strategy for autonomous, real-time hazard detection during the approach trajectory utilizes a 2-D array lidar sensor to rapidly generate a high resolution, 3-D terrain model in proximity to the nominal landing target. This map can be generated and processed in a vehicle or sensor coordinate frame, or transformed to a planetary coordinate frame in the form of a DEM. The ALHAT team referred to this product as the Hazard DEM (HDEM) to differentiate it from the Reconnaissance DEM (RDEM) used for TRN position measurements. The HDEM is parsed for local slope and roughness to develop a “cost map” based on a weighting function of critical landing parameters, including lander hazard tolerances and the required divert distance. The ranked list of safe landing targets is passed from the hazard detection system (HDS) to the lander GN&C system, which then executes a divert to the selected safe site. When an HDEM is generated, a relationship is established between the spacecraft inertial state and the coordinates of the selected safe landing target. A safe landing is achieved by accurately propagating the lander navigation state from HDEM generation through terminal descent to a controlled touch down in close proximity to the selected landing target. The ALHAT team often referred to the landing error with respect to the selected safe landing target as “local landing precision” to differentiate it from the “global landing precision” function supported by TRN relative to the pre-mission defined landing target.

The dimensions of an HDEM must span multiple, non-overlapping, potential landing areas in order to provide an acceptable probability of locating at least one safe landing site. As a result, the lander footprint and local landing precision impact both the frequency of available safe landing sites and the required size of the HDEM. As the variability in the roughness and slope of the surface increases, the size of the HDEM must also increase to maintain a given probability of safe landing. Larger HDEMs place more challenging performance requirements on the HD lidar sensor, processing electronics, and beam steering system, and typically involve longer data acquisition and processing times. As a result, the ALHAT team selected a challenging, but achievable, local landing precision requirement of three meters (3σ) relative to the selected landing target to minimize the required diameter of the safe landing site. The velocity measurement precision provided by the NDL sensor is critical to meeting this local landing precision requirement.

For many missions, the augmentation of the core GN&C sensor suite with an NDL sensor may be sufficient to achieve the desired local landing precision. However, the ALHAT team devised a supplemental navigation technique called Hazard Relative Navigation (HRN) to assist in controlling position error growth during the approach phase. Although HRN is functionally quite similar to TRN, the key difference is that TRN utilizes stored maps derived from orbital

reconnaissance data registered in the planetary frame. TRN maps for lunar and Mars applications will typically provide a ground spatial distance (GSD) on the order of tens of meters for regional DEMs, and 5 to 10 meters for smaller (100 to 400 square km) local DEMs. HRN, in contrast, utilizes the high resolution HDEM (~10cm GSD) generated by the HD lidar sensor during the approach phase. Assuming that the HD lidar sensor is capable of acquiring additional images within the boundaries of the HDEM using beam steering or an appropriate vehicle attitude profile, these images can be correlated with the HDEM to update the position of the spacecraft relative to the selected safe landing target. A navigation filter processing HRN position measurements in combination with NDL velocity measurements is expected to produce an extremely accurate lander navigation state heading into terminal descent, thus supporting the ALHAT strategy of dead reckoning to a precise and controlled landing. The repurposing of the HD lidar sensor and the HDEM to produce HRN measurements is appealing from an engineering standpoint. However, additional analysis, simulation, and testing is needed to quantify the costs and benefits of HRN as part of a comprehensive PL&HA strategy.

Approach and Landing

Over the past decade, the ALHAT team has demonstrated through analysis, simulation, and testing that the augmentation of a lander GN&C system with high precision lidar sensors for ranging and velocimetry significantly improves surface relative navigation performance. This translates to a range of benefits, from improvements in landing precision and stability to higher efficiencies in landing gear design efficiency. The modular and flexible PL&HA strategy developed by the ALHAT team is applicable to a variety of solar system destinations and EDL trajectories. The execution of a precise and controlled touch down at the selected safe site is the final step in the PL&HA challenge.

The dust field kicked up by the rocket engine exhaust during powered descent and landing obscures the view of the planetary surface for onboard spacecraft sensors. The extent of the dust field is influenced by the lander propulsion system configuration, soil/rock characteristics of the landing site, presence or absence of an atmosphere, and the landing trajectory profile. Dust obscuration was a significant challenge during several of the Apollo landing missions, even given favorable lighting conditions for human vision and the judgment and control provided by well-trained crew. Dust obscuration during terminal descent may present an even greater challenge for automated robotic or cargo landers. One risk mitigation option is to reduce soil disturbance by dividing the landing thrust among a larger number of engines and canting those engines outwards, as on the Mars Viking lander. But larger, human-scale exploration landers will require much greater total thrust such that even a large number of thrusters may not adequately disperse the rocket exhaust. Another mitigation option, used on both MSL and Mars 2020, is to orient landing sensor beams to point over the anticipated dust field at more distant terrain. However, MSL and Mars 2020 employ a sky crane landing strategy in which the payload is lowered to the surface on a tether with subsequent disposal of the propulsive stage. For a

monolithic lander design, sensor obscuration from dust will occur at some point during terminal descent, even with outwardly canted sensors. A third option is to attempt to obtain useful radar or lidar sensor measurements through the dust using oversampling and filtering. However, it is likely to be technically challenging to collect and process such measurements. None of these options fully mitigate the risks associated with the dust field generated during landing, and all of them involve significant design, analysis, test, and certification efforts. A fourth mitigation option favored by the ALHAT team due to its simplicity and effectiveness is to establish a high quality navigation state prior to terminal descent, followed by inertial propagation (i.e., dead reckoning) during the final tens of meters/tens of seconds to avoid the requirement for sensing through or around the dust field. ALHAT analyses indicate that a precision touch down within a few meters of a target selected during the approach phase is achievable.

Additional Landing Risks

In the PL&HA strategy described above, the safe landing target is identified using an HDEM generated by an onboard 3-D lidar sensor during the approach phase. A key assumption in this approach is that the selected landing site remains safe through terminal descent and landing. If the planetary surface is significantly reshaped or destabilized by the descent engine exhaust plume(s) during terminal descent, then the safety analysis based on the HDEM may be invalidated. Another key assumption is that the landing area is free from shallow, subsurface voids and other soil instabilities that might result in a collapse during or after touch down.

These landing risks can be mitigated by one or more of the following options:

- Lander propulsion system design
- Terminal descent profile design
- Enhanced landing site evaluation to assess subsurface characteristics
- Landing site preparation via excavation and grading
- Landing pad construction using locally sourced materials

A landing site with exposed bedrock or shallow soil over bedrock is preferred. It may be possible to adequately assess local subsurface conditions via orbital reconnaissance. If not, then a rover using ground penetrating radar or other sensing techniques would be required. Landing risk mitigation options involving site preparation or pad construction would require complex precursor missions, but the benefits may outweigh the costs for a multi-mission exploration campaign.

PL&HA Strategies

Spacecraft design involves a series of difficult compromises among mission objectives, technical considerations, and programmatic guidance and constraints. Payload requirements bump up against available launch vehicle performance, payload fairing dimensions, and spacecraft mass. And mission cost and schedule nearly always exceed initial estimates. Risks are difficult to quantify and even more difficult to manage and mitigate. In this complex environment, PL&HA

functions must be applied in a modular and logical manner to facilitate mission objectives while also satisfying programmatic and lander constraints.

Robotic landers tend to be much smaller in scale than human or cargo exploration vehicles, and more sensitive to the SWaP of each subsystem and component. Robotic landers also tend to be highly cost-constrained and tightly focused on a small set of mission objectives. Available spacecraft resources are typically concentrated on the science payload, and every component must pass a rigorous cost/benefit analysis. However, if the mission design is compatible with TRN and sufficient reconnaissance data is available, then mission planners and spacecraft designers should seriously consider incorporating TRN. Passive optical TRN provides substantial mission benefits with minimal SWaP and complexity impacts to the spacecraft.

If there is insufficient *a priori* reconnaissance data available to support TRN at the destination, then there are three potential options for a robotic lander. The first option is to emphasize robustness in the lander design and pursue a traditional blind landing. The second option is to accept a large landing dispersion envelope, but employ onboard hazard detection to improve the probability of a safe landing. The third option is to incorporate an orbital trajectory phase to collect the necessary TRN data. After the reconnaissance data is processed and the TRN maps and landing target are uploaded to the spacecraft, the mission can proceed using TRN for precision landing, with or without onboard hazard detection.

On crewed missions, onboard GN&C capabilities can be supplemented with human senses, training, and judgment to perform complex operations. During the Apollo landing missions, GN&C designers improved inertial navigation performance by incorporating a basic form of TRN in which time measurements from astronaut observations of key surface features passing across inscribed references on the LEM window indicated if the lander was ahead or behind in the trajectory profile. Rather than attempting to modify the LEM navigation state, these observations were used in guidance to bias the landing target uprange or downrange to improve landing precision relative to the pre-mission selected target. This approach compensated for the relative error between the onboard navigation state estimate and the surface relative position estimate provided by the astronaut observations without impacting the operation of the navigation filter. Human senses and judgment were also employed during the approach and landing phases of the lunar trajectory to select a safe landing site and guide the LEM to a safe, controlled touch down. Even with extensive training, however, these tasks proved to be highly challenging for the Apollo astronauts. The visual cues at the Moon conflicted with a lifetime of learned behavior on Earth, and this is likely to be true at other exploration destinations, as well. In addition, physical debilitation during the much longer transit times to Mars and other solar system bodies is likely to adversely impact crew performance during the EDL phase of the mission. Modern sensors, software, and data processing capabilities can assist in efficiently automating the PL&HA functions that were handled by astronauts during the Apollo program. Autonomous PL&HA capabilities are a

natural starting point for a human exploration program, but the future role of onboard PL&HA depends on NASA's investment plans in precursor missions to characterize candidate landing areas and emplace navigation aids.

Human exploration missions fall into two basic categories – short duration sortie missions involving a single lander and extended duration exploration missions involving a coordinated series of crew and cargo landers. In the case of a sortie mission, an autonomous PL&HA system is likely to play a primary GN&C role. More ambitious planetary exploration programs, such as the NASA Evolvable Mars Campaign (EMC), require multiple landings to establish a base of operations, followed by a series of crew rotations and logistics deliveries throughout the life of the Mars base. Orbital navigation assets can be deployed during each mission, and beacons can be included on every EMC lander and dispersed by rovers to improve local navigation capabilities. Over time, navigation at other solar system destinations will evolve to more closely resemble modern GPS-based navigation at Earth. During this evolution, some autonomous PL&HA sensors and functions may be eliminated from the GN&C systems on robotic landers to reduce mass, power, complexity, and cost. On human landers and high-value cargo landers, however, autonomous PL&HA functions may be retained to provide redundancy in the event of a loss of communication links.

EDL Trajectories

The mission epoch and EDL trajectory design will impact the availability and utility of onboard PL&HA functions and external navigation aids for both individual missions and multi-mission campaigns. In order for navigation satellites to be effective, a sufficient number of satellites must be available in a geometry that satisfies the navigation error constraints for a given spacecraft entry corridor. In order for surface beacons to be effective, the geometric dispersion of the beacons along the ground track must satisfy line-of-sight visibility requirements and cross-track displacement at critical segments of the EDL trajectory. Similarly, adequate ambient lighting must be available along the EDL ground track to support onboard passive optical TRN, along with the necessary stored reconnaissance maps and appropriate sensor orientation. A shallow and fast approach trajectory will limit visibility of the target area for hazard detection, and will also reduce the time available to generate and process the HDEM and implement the hazard avoidance divert maneuver.

The EDL trajectory design and the preferred PL&HA solution will vary with the type of mission and the mission destination, including the presence or absence of an atmosphere, strength of the gravity field, availability and quality of *a priori* reconnaissance data, surface visibility from orbit and at different altitudes during EDL, and many other considerations. The costs, benefits, and capabilities of onboard and external navigation aids must be evaluated in terms of the mission objectives and the EDL trajectory design. What are the impacts of lander L/D and other design characteristics? When are position, altitude, and velocity measurements available during the EDL trajectory to address the precision

landing requirement? What lander aerodynamic and propulsive capabilities are available to control and eliminate position dispersions during the EDL trajectory?

Mars is an interesting use case, combining a thin atmosphere with a substantial gravity well. Assuming inertial propagation during the hypersonic phase of Mars EDL, large position dispersions will accumulate that must be flown out during the latter phases of EDL to achieve pinpoint landing. The earlier that these navigation knowledge errors can be reduced and the more that the trajectory can be corrected using aerodynamic control, the more mass efficient it will be to achieve pinpoint landing at Mars. Small robotic landers generally employ parachute deceleration during the latter stages of a Mars EDL trajectory, resulting in a mostly vertical descent with lateral wind drift prior to a brief propulsive deceleration phase. Several terminal descent strategies have been employed for robotic landers at Mars, including propulsive landing, air bags, and the MSL sky crane approach. Larger Mars crew and cargo landers are likely to transition directly from aerodynamic entry to supersonic retro propulsion (SRP). The transition to SRP may begin at only a few kilometers above the surface of Mars, resulting in high, lateral surface relative velocities at low altitudes, followed by a brief propulsive landing phase.

External Navigation Aids

It is reasonable to anticipate that orbital navigation satellites and surface beacons will eventually play a major role in PL&HA for human exploration. But a coordinated, long term effort to emplace the necessary navigation assets will be required, and these assets will have to be maintained over an extended period of time.

Surface beacons can be passive or active, and may utilize radio and/or optical wavelengths. Every beacon will have to be surveyed into the planetary coordinate frame, and a unique identifier will be encoded on the active or passive signal to link it with its registered location. It is possible that radar or lidar sensors developed to support autonomous PL&HA functions could also be used to interrogate passive beacons mounted on landers and rovers, or deployed on the planetary surface.

Every future landing mission – robotic precursor, cargo delivery, and human – should include one or more beacons to add navigation fiducials at key exploration destinations. Rovers can be used to distribute arrays of surface beacons to support future landing missions.

Landing Site Surveys and Surface Preparation

For exploration campaigns involving multiple missions to a common destination, robotic precursors missions will be used to survey prospective terrain for safe landing sites and establish ground transit corridors between landing sites. Larger and more capable rovers could be used to improve or prepare landing areas by shifting moderate-size rocks and grading the soil to eliminate surface roughness or remove loose material. The next step beyond simple excavation and grading would be the automated construction of landing pads, blast ejecta berms, walls,

and other useful infrastructure using *in situ* materials.

If, prior to initial crew or cargo landing missions, rovers are employed to perform high resolution terrain surveys sufficient to identify specific landing targets that are safe for a particular lander or class of landers, then an autonomous hazard detection system may not be required. In this case, a precise and controlled landing is equivalent to a safe landing, and a combination of TRN and one or more surface beacons in proximity to each landing site may be adequate for a broad range of missions. After locating one safe landing target, a rover could follow an outward spiral or pre-programmed search pattern to establish a series of safe landing targets.

Forward Path

The development and maturation of autonomous PL&HA technologies over the past decade has provided mission planners and spacecraft designers with important new capabilities for robotic, cargo, and human landing missions on solid solar system bodies.

Passive optical TRN has a long history of successful Earth-based applications and will be demonstrated on the upcoming Mars 2020 and Resource Prospector missions. Space-qualified cameras and optics are commercially available, and passive optical TRN offers a very attractive combination of performance, low SWaP, and relatively low cost. The expectation is that passive optical TRN will be widely adopted on future science and exploration missions.

Through COBALT and other ongoing development and testing activities, NASA continues to invest in the evolution of sensors, algorithms, and processing capabilities for autonomous PL&HA. The LaRC Navigation Doppler Lidar sensor is a highly attractive candidate for the next generation of ranging and velocimetry instruments for spaceflight. The integration and testing of the LVS and NDL on the upcoming COBALT flights will demonstrate an effective and efficient surface relative navigation system for controlled precision landing. NASA also continues to pursue the advancement of 3-D terrain mapping lidar sensors to support real-time hazard detection and avoidance.

As NASA progresses towards long duration human exploration missions at Mars and other destinations, autonomous PL&HA capabilities will gradually be supplemented with highly detailed surface knowledge and external navigation aids, such as navigation satellites and surface beacons. The result will be highly capable and robust PL&HA capabilities for robotic and human exploration of the solar system.

Acknowledgements

This paper is largely based on experience gained through the multi-center ALHAT project. I wish to extend my heartfelt appreciation to all of the NASA and contractor personnel who supported ALHAT development, integration, and testing efforts over the years. Special thanks go to Dr. Chirold Epp, who so ably

led the ALHAT team from its inception in 2006 through the final Morpheus-ALHAT flight in December 2014.

Every new capability builds on the work of our predecessors, so it is also important to acknowledge the importance of the extensive terrestrial background in autonomous PL&HA capabilities that we are in the process of extending to the Moon, Mars, and beyond.

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